UNITED STATES DEPARTMENT OF AGRICULTURE
GRAIN INSPECTION, PACKERS AND STOCKYARDS ADMINISTRATION

Unified Grain Moisture Algorithm

Recipe Book

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UNIFIED GRAIN MOISTURE ALGORITHM

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Introduction

The purpose of this document is to present a concise and precise description of GIPSA's Unified Grain Moisture Algorithm (UGMA) and associated equations for use by entities who are involved in developing and seeking FGIS certification for UGMA-compatible grain moisture meters. An even more detailed explanation of the method (for those without considerable familiarity with the UGMA) is available upon request.

UGMA Steps

1. Measure the dielectric constant (ε_{meas}) of the grain at a defined frequency near 149 MHz using a parallel-plate transmission line test cell of dimensions similar to those of the FGIS master cell and a loading method that provides for operator-independent measurements.
2. Measure the *Mass* of the grain within the defined volume of the test cell (*TestCellVolume*).
3. Apply the Landau-Lifshitz, Looyenga-based density normalization (1) to transform the measured dielectric constant to density-corrected dielectric constant (ε_{den}) with a common density basis (ρ_{target}= 0.67405 g/ml) for all grain types.

$$\boldsymbol{\varepsilon_{den}} = \left[\left(\boldsymbol{\varepsilon_{meas}^{1/3}} - \mathbf{1}\right) \cdot \frac{\boldsymbol{\rho_{target} \cdot TestCellVolume \cdot VR_s}}{\boldsymbol{Mass}} + \mathbf{1}\right]^{\mathbf{3}} \tag{1}$$

(Note: Grain-group-specific volume ratio factors (VR_s) may need to be inserted as multipliers in the target mass calculation (target density times test cell volume) to compensate for slight differences in loading methods among instrument models. The *s* subscripts refer to grain-group-specific parameters.)

4. Apply grain-group-specific unifying parameters: Slope parameter (SP_s), Translation parameter (TP_s), and Offset parameter (OPo_s) (Table 2 or Table 3 depending on the chosen reference temperature) to the density-corrected dielectric constant as in Eq. 2a.

$$\boldsymbol{\varepsilon_{adj}} = (\boldsymbol{\varepsilon_{den}} - \boldsymbol{OPo_s}) \cdot \boldsymbol{SP_s} + \mathbf{2.5} + \frac{\boldsymbol{TP_s}}{\mathbf{6}} \tag{2a}$$

There is a mathematically simpler form (Eq. 2b) that is equivalent (as far as performance) but requires different numerical values of the Offset unifying parameter (OP_s). (Both OPo_s (original form) and the equivalent OP_s values are listed in Tables 2 and 3.) Note that the Translation parameter TP_s does not appear in Eq. 2b.

$$\varepsilon_{adj} = \varepsilon_{den} \cdot SP_s + OP_s \tag{2b}$$

Transformations between the two sets of Offset unifying parameters are performed as in Eq. 2c and 2d.

$$OP_s = -OPo_s \cdot SP_s + 2.5 + \frac{TP_s}{6} \tag{2c}$$

$$OPo_S = \frac{-OP_S + 2.5 + \frac{TP_S}{6}}{SP_S} \tag{2d}$$

5. Calculate the initial moisture estimate (*Moisture 1*) from the adjusted dielectric constant using the 5th order polynomial calibration (Eq. 3), where *KCC* is the vector of polynomial coefficients.

$$\boldsymbol{Moisture1} = \sum_{i=0}^{5}\left(\boldsymbol{KCC_i} \cdot \boldsymbol{\varepsilon_{adj}^{i}}\right) \tag{3}$$

6. Using Eq. 4, apply the translation parameter (TP_s, moisture axis shift) to get the predicted moisture (prior to temperature correction) (*Moisture2*).
7.

$$Moisture2 = Moisture1 - TP_s \tag{4}$$

8. Apply the temperature correction function (Eq. 5). (Notes: The temperature correction function (Eq. 7), a function of temperature and moisture, may use from one to three coefficients depending on the nature of the correction required. The form of Eq. (5), used here and below, is meant to state that the *TempCorr* is a function involving parameters *Temperature* and *Moisture 2*.)

$$Moisture3 = Moisture2 - TempCorr(Temperature, Moisture2) \tag{5}$$

9. Apply the secondary kernel-density correction (as yet, only needed for corn) to obtain the final predicted moisture result.

$$MoistureFinal = Moisture3 - SecDensCorr(Moisture3, Mass) \tag{6}$$

Measured Values: (Note: These are critical measured parameters for demonstrating conformance with the UGMA.)

- ε_{den}: density-corrected dielectric constant at approximately 149 MHz
- Sample temperature
- Sample mass

Unifying Parameters

Three grain-group-dependent parameters are necessary to use the same polynomial calibration (basic calibration curve shape) for all grain groups. Unifying parameters are derived using an optimization algorithm that FGIS will provide upon request as an Excel file.

- OP_s: Offset parameter
- SP_s: Slope parameter
- TP_s: Translation parameter

Calibration Coefficients

The calibration is the relationship between the adjusted dielectric constant and reference moisture content (back-corrected for sample temperature and secondary kernel-density correction and adjusted by the translation parameter). For corn there is no adjustment because of the unifying parameters are *OP*=0, *SP*=1 and *TP*=0. *KCC* is the vector containing the coefficients of the fifth order polynomial calibration equation.

For the current calibration curve, only the normal kernel-density corn samples were used from the 2008, 2009, and 2010 crop years. However, 30 dry corn samples between 7.4% and 11.2% were added to refine the shape of the low moisture range. A dummy point (adjusted dielectric constant=10; adjusted moisture= 65) was added to extend the calibration curve to extremely high dielectric constant levels without "roll-over." Adding this point did not significantly change the performance of the calibration, but it extended the calibration curve to give reasonable results for grains and commodities whose adjusted dielectric constants approach 10 (approximately 50% M grain).

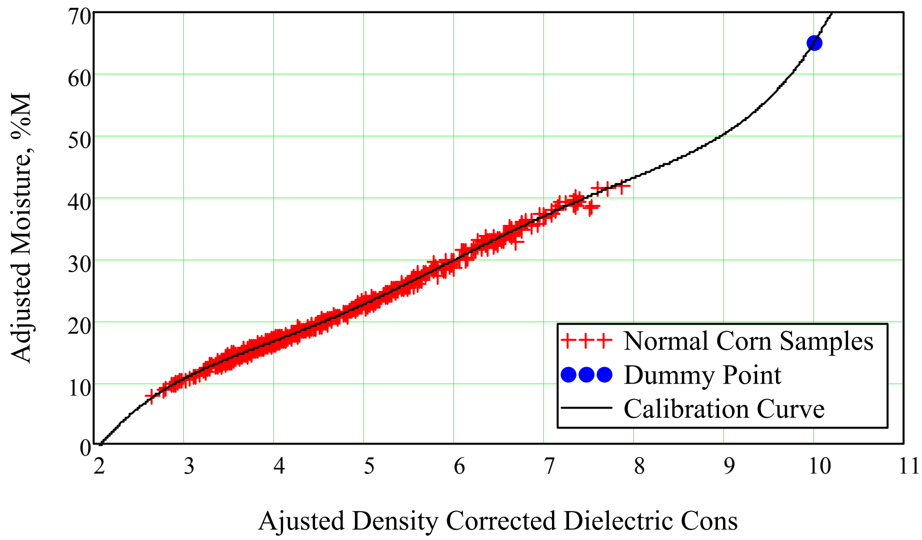


Figure 1. Calibration curve

Temperature Correction

Temperature correction is applied to the predicted moisture to minimize the effect of sample temperature—that is, to cause the final moisture estimate to closely match the estimate that would be given for that sample if measured at room temperature (22°C or 25°C). FGIS is developing temperature corrections over a wide temperature range (from -18°C to 48°C.) The UGMA exhibits a significant advantage (relative to most other moisture meters) in its ability to accurately predict moisture content for grain (at normal market moisture levels) at temperatures well below 0°C. The form of the correction can be moisture level dependent and may be linear or quadratic with temperature. In this document we share the KTC_s coefficients for the simple linear form ($KTCS_s$=$KTCQ_s$=0). Achieving accuracy over wide moisture and temperature ranges will probably require one of the two more complex forms (with $KTCS_s$ and/or $KTCQ_s$ non-zero).

$$Moisture3 = \frac{Moisture2 - KTC_s \cdot (T - TTC) - KTCQ_s \cdot (T - TTC)^2}{1 + KTCS_s \cdot (T - TTC)} \quad (7)$$

The target temperature (*TTC*) was changed from 25°C to 22°C because 22°C is the nominal room temperature for all the calibration sample tests at FGIS. Making the target temperature equal to the nominal room temperature minimizes the interaction between the temperature coefficients and the unifying parameters and polynomial calibration coefficients.

The listed temperature correction coefficient (KTC_s) values (see Tables 2 and 3) were estimated from FGIS tests done in 2007, 2009, and 2010 using a special insulated test cell (GP test cell) and the HP-4291A Impedance Analyzer. The values previously obtained by Peter Meszaros (with a less-refined prototype system) were also considered, but the HP-4291A data are more reliable. As yet, we have too few data points and an insufficiently wide temperature range to assign definitive moisture-dependent or moisture-dependent with quadratic temperature correction coefficients, so only moisture-independent KTC_s values are listed here.

Secondary Kernel-Density Correction

The secondary kernel-density correction is applied to the predicted moisture to reduce the error caused by extremely low kernel-density (low quality). This correction appears to be unnecessary for grain types other than corn. The correction (Eq. 8) was developed by Zoltan Gillay in 2010 and was published at the ISEMA 2011 Conference in Kansas City in June 2011. Additional details are shown on page 13. Note that both the *TargetDensity* and the *SlopeCorrection* values are moisture-dependent and are found by linear interpolation from the TD Table (Table 6) and SC Table (Table 7), respectively.

$$SecDensCorr(Moisture3, Mass) = \left(\frac{Mass}{TestCellVolume} - TargetDensity\right) \cdot SlopeCorrection \quad (8)$$

Where:

$$TargetDensity = LinearInterpolation(TDTable, Moisture3) \quad (9)$$

$$SlopeCorrection = LinearInterpolation(SCTable, Moisture3) \quad (10)$$

Parameters, Coefficients, and Grain Groups

The parameters may be refined annually as FGIS conducts tests on additional samples. Some further changes may be made before May 2012.

The full numeric resolution shown in the tables is necessary to agree with FGIS results within 0.01% M.

The first nine (soybeans, sorghum, sunflower, corn, oats, wheat, durum, barley, long grain rough rice) grain groups are the "major" grains. The others grain groups (and their parameters) are still subject to revision as more samples of "minor" grain types are tested. The beans and processed rice groups show some scatter among individual grain types; the grouping of edible bean and processed rice types is expected to be refined based on further data. Grain types marked with an asterisk (*) have been assigned tentatively to groups based on data obtained using the original larger UGMA grain test cell, but they have not been tested with the current standard test cell.

Table 1. Grain types within grain groups listed alphabetically by grain type

Major Groups	Grain Type Names
1. Soybeans	Soybeans
2. Sorghum	Sorghum
3. Sunflower	Sunflower Seed, Oil-type
	Sunflower Seed, Confectionary (minor grain)
4. Corn	Corn
	Popcorn * (minor grain)
	Corn, Waxy * (unlisted grain)
	Corn, Hi-Oil * (minor grain)
5. Oats	Oats
	Oats, Hull-Less* (unlisted grain)
6. Wheat	Wheat, Hard White
	Wheat, Soft White
	Wheat, Hard Red Spring
	Wheat, Soft Red Winter
	Wheat, Hard Red Winter
7. Durum	Durum
8. Barley	Barley, Six-Rowed
	Barley, Two-Rowed
9. Rice, Long Rough	Rice, Long Grain Rough
10. Rice, Medium Rough	Rice, Medium Grain Rough

Minor Groups	Grain Type Names
11. Rice, Short Rough	Rice, Short Grain Rough
12. Rice, Processed	Rice, Long Grain Milled
	Rice, Medium Grain Milled
	Rice, Long Grain Brown
	Rice, Medium Grain Brown
	Rice, Brewers Milled *
	Rice, Long Grain Brown Parboiled *
	Rice, Short Grain Brown *
	Rice, Second Head Milled Parboiled *
	Rice, Long Grain Milled Parboiled *
	Rice, Long/ Medium Second Head Milled *
	Rice, Medium Grain Milled Parboiled *
	Rice, Medium/ Short Second Head Milled *
	Rice, Brewers Milled Parboiled *
	Rice, Short Grain Milled *
	Rice, Short Grain Second Head Milled *
	Rice, Medium Grain Brown Parboiled *
	Rice, Screenings Milled *
	Rice, Short Grain Milled Parboiled *
13. Beans 1	Beans, Blackeye
	Beans, Pinto
	Beans, Cranberry
	Beans, Pink
	Lentils
	Peas, Split *
	Beans, Dark/ Light Red Kidney
14. Beans 2	Beans, Baby Lima
	Beans, Garbanzo
	Beans, Small Red
	Beans, Yelloweye *
	Beans, Small White *
	Beans, Pea
15. Beans 3	Beans, Black
	Beans, Great Northern
	Beans, Large Lima
16. Peas	Peas, Austrian Winter *
	Peas, Smooth Green Dry
	Peas, Wrinkled Dried *
17. Safflower	Safflower
18. Canola	Canola
	Rapeseed *
19. Mustard	Mustard Seed, Yellow
	Mustard Seed, Oriental
20. Triticale&Rye	Triticale*
	Rye
21. Flaxseed	Flaxseed

Table 2. Unifying parameters and linear temperature correction coefficients for each grain group with target temperature *TTC* = 22°C. (*OP* for Eq. 2b, *OPo* for Eq. 2a)

Grain Group	***OP* 22°C**	***OPo* 22°C**	***SP* 22°C**	***TP* 22°C**	***KTC***
Soybeans	0.68444	2.23060	0.85832	0.59400	0.091
Sorghum	-0.23909	2.48283	1.16678	0.94690	0.100
Sunflower	1.36767	2.88370	0.57039	3.07510	0.050
Corn	0.00000	2.50000	1.00000	0.00000	0.108
Oats	0.08696	2.43533	1.09845	1.57230	0.100
Wheat	-0.20442	2.43461	1.15451	0.63810	0.110
Durum	-0.22846	2.50045	1.18166	1.35740	0.110
Barley	0.20121	2.10579	0.89427	-2.49390	0.100
Rice, Long Rough	-0.40705	2.50732	1.10135	-0.87360	0.100
Rice, Medium Rough	-0.51342	2.47931	1.13624	-1.17790	0.070
Rice, Short Rough	-0.65349	2.42490	1.15304	-2.14490	0.100
Processed Rice	-0.09677	2.59727	1.17989	2.80640	0.100
Beans 1	0.47529	2.06085	0.81333	-2.09140	0.108
Beans 2	0.36191	2.12185	0.89235	-1.46800	0.108
Beans 3	0.28697	2.10582	0.94366	-1.35510	0.108
Peas	0.22744	1.99826	0.93946	-2.37160	0.081
Safflower	0.89338	2.77002	0.70336	2.05020	0.054
Canola	0.83104	2.74589	0.80647	3.27320	0.054
Mustard	0.86320	2.23787	0.67149	-0.80460	0.108
Triticale&Rye	0.20082	2.25944	1.01759	0	0.100
Flaxseed	0.95661	2.636	0.65649	1.1228	0.080

Table 3. Unifying parameters and linear temperature correction coefficients for each grain group with target temperature *TTC* = 25°C. (*OP* for Eq. 2b, *OPo* for Eq. 2a) (Note: These values are provided for historical purposes and should not be incorporated into new instrument designs.)

Grain Group	***OP*** **25°C**	***OPo*** **25°C**	**SP 25°C**	**TP 25°C**	**KTC**
Soybeans	0.67857	2.22955	0.86081	0.58670	0.091
Sorghum	-0.24995	2.48561	1.16987	0.94740	0.100
Sunflower	1.36434	2.84414	0.57202	2.94750	0.050
Corn	0.00000	2.50000	1.00000	0.00000	0.108
Oats	0.07845	2.43832	1.10178	1.58970	0.100
Wheat	-0.21248	2.44215	1.15803	0.69350	0.110
Durum	-0.23644	2.50780	1.18582	1.42430	0.110
Barley	0.19324	2.11579	0.89910	-2.42670	0.100
Rice, Long Rough	-0.41558	2.51073	1.10413	-0.86050	0.100
Rice, Medium Rough	-0.52199	2.46931	1.13889	-1.25830	0.070
Rice, Short Rough	-0.66284	2.42882	1.15610	-2.12930	0.100
Processed Rice	-0.10769	2.59968	1.18378	2.81860	0.100
Beans 1	0.46880	2.07565	0.81750	-2.00620	0.108
Beans 2	0.35529	2.13464	0.89675	-1.38280	0.108
Beans 3	0.28011	2.11580	0.94705	-1.29680	0.108
Peas	0.22210	1.99533	0.94294	-2.37860	0.081
Safflower	0.89066	2.74276	0.70577	1.95850	0.054
Canola	0.82740	2.72121	0.80939	3.17950	0.054
Mustard	0.85982	2.25387	0.67467	-0.71740	0.108
Triticale&Rye	0.19528	2.26193	1.01892	0.00000	0.100
Flaxseed	0.95723	2.62254	0.65563	1.05980	0.080

Table 4. UGMA 5th order polynomial coefficients with 22°C target temperature.

Exponent	***KCC @ TTC* = 22°C**
0	-109.637
1	108.0978
2	-39.07601
3	7.153181
4	-0.6263259
5	0.02111302

Table 5. UGMA 5th order polynomial coefficients with 25°C target temperature. (*Obsolete*)

Exponent	***KCC @ TTC* = 25°C**
0	-110.335
1	108.5338
2	-39.2476
3	7.184863
4	-0.62922
5	0.02122

Table 6. Secondary kernel-density correction target density lookup table (*TDTable*) to determine the *Target Density* value by linear interpolation. *Moisture3* is the temperature-corrected predicted moisture (Eq. 7).

Moisture3	***Target Density***
0	0.7168
15	0.7168
17	0.7116
19	0.7018
27	0.6451
30	0.6297
33	0.6253
100	0.6253

Table 7. Secondary kernel-density correction *Slope Correction* lookup table (*SC Table*) to determine the *Slope Correction* value by linear interpolation. *Moisture3* is the temperature-corrected predicted moisture (Eq. 7).

Moisture3	***Slope Correction***
0	10.4
13	10.4
33	-17
100	-17

Performance Statistics

The statistics represent all samples that were available as of February 1, 2011.

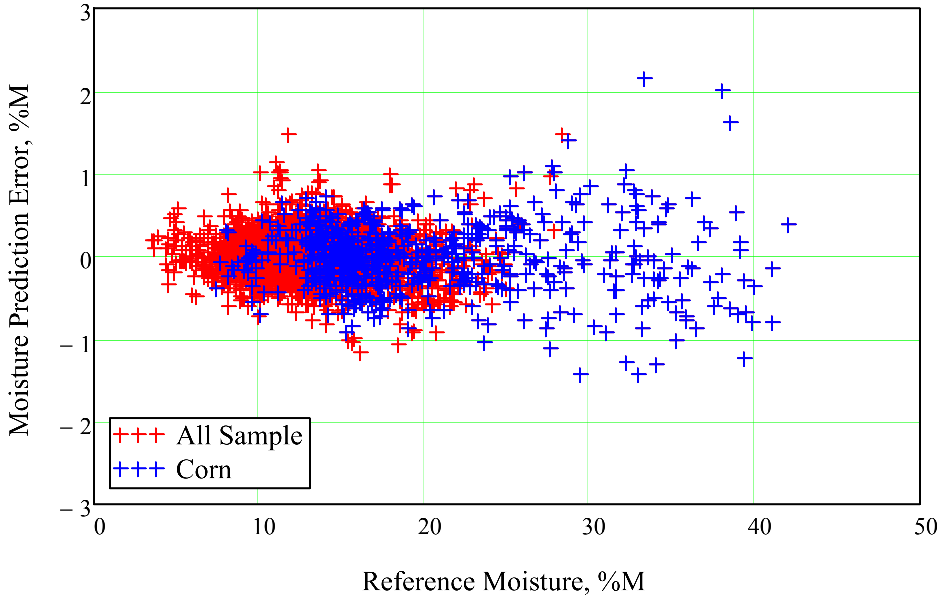


Figure 2. UGMA moisture prediction errors with respect to air oven moisture for all grain samples for 2008, 2009, and 2010 crop years.

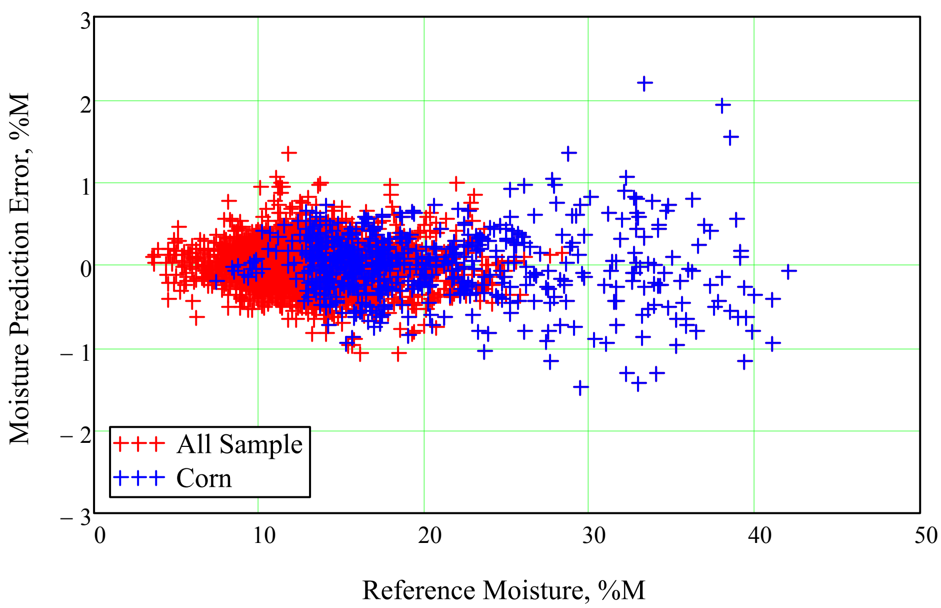


Figure 3. Individual calibrations' (per grain group) moisture prediction errors with respect to air oven moisture for all grain samples from 2008, 2009, and 2010 crop years. The purpose of showing this graph (and associated statistics) is to demonstrate that using a common calibration curve for all grain types is not limiting the achievable performance of the method.

Table 8. UGMA calibration statistics by grain groups. STD is the standard deviation of predicted moisture error for the calibration samples. Slope is the slope of the predicted moisture errors.

Grain Group	Samples	Bias	STD	Slope	Moisture Range
Soybeans	345	0.00	0.20	-0.01	8 - 23
Sorghum	144	0.00	0.22	-0.01	10 - 24
Sunflower	246	0.00	0.38	-0.02	5 - 20
Corn	668	-0.01	0.41	0.00	7 - 42
Oats	66	0.00	0.28	-0.06	10 - 18
Wheat	1009	0.00	0.19	-0.01	7 - 22
Durum	130	0.00	0.18	0.00	5 - 19
Barley	238	0.00	0.27	-0.02	8 - 18
Rice, Long Rough	226	0.00	0.32	-0.01	10 - 26
Rice, Medium Rough	139	0.00	0.35	-0.01	10 - 28
Rice, Short Rough	18	0.00	0.46	-0.02	12 - 24
Processed Rice	99	0.00	0.19	-0.04	10 - 15
Beans 1	114	0.00	0.22	-0.01	8 - 20
Beans 2	63	0.00	0.19	0.00	7 - 19
Beans 3	71	0.00	0.22	-0.01	10 - 21
Peas	72	0.00	0.20	-0.01	9 - 16
Safflower	30	0.00	0.20	-0.01	3 - 12
Canola	15	0.00	0.12	-0.01	4 - 9
Mustard	14	0.00	0.29	0.00	5 - 19
Triticale&Rye	4	0.00	0.02	0.00	12 - 13
Flaxseed	9	0.00	0.04	-0.01	7 - 9

Table 9. Calibration statistics for calibrations created for individual grain groups. (Instead of UGMA, 5th order polynomials were fitted to each grain group.)

Grain Group	Samples	Bias	STD	Slope	Moisture Range
Soybeans	345	0.00	0.20	-0.01	8 - 23
Sorghum	144	0.00	0.22	-0.01	10 - 24
Sunflower	246	0.00	0.38	-0.02	5 - 20
Corn	668	0.00	0.41	0.00	7 - 42
Oats	66	0.00	0.28	-0.06	10 - 18
Wheat	1009	0.00	0.19	-0.01	7 - 22
Durum	130	0.00	0.18	0.00	5 - 19
Barley	238	0.00	0.27	-0.02	8 - 18
Rice, Long Rough	226	0.00	0.32	-0.01	10 - 26
Rice, Medium Rough	139	0.00	0.35	-0.01	10 - 28
Rice, Short Rough	18	0.00	0.46	-0.02	12 - 24
Processed Rice	99	0.00	0.19	-0.04	10 - 15
Beans 1	114	0.00	0.22	-0.01	8 - 20
Beans 2	63	0.00	0.19	0.00	7 - 19
Beans 3	71	0.00	0.22	-0.01	10 - 21
Peas	72	0.00	0.20	-0.01	9 - 16
Safflower	30	0.00	0.20	-0.01	3 - 12
Canola	15	0.00	0.12	-0.01	4 - 9
Mustard	14	0.00	0.29	0.00	5 - 19
Triticale&Rye	4	0.00	0.02	0.00	12 - 13
Flaxseed	9	0.00	0.06	-0.02	7 - 9

Table 10. UGMA calibration statistics by individual grain type

Grain Types	Samples	Bias	STD	Slope	Moisture Range
Barley, Six-Rowed	117	-0.05	0.28	-0.01	8 - 17
Barley, Two-Rowed	121	0.05	0.25	-0.03	9 - 18
Beans, Baby Lima	20	-0.13	0.19	0.11	10 - 12
Beans, Black	20	0.16	0.26	-0.04	10 - 18
Beans, Black-Eyed	21	-0.11	0.14	-0.07	9 - 13
Beans, Cranberry	10	-0.17	0.16	0.01	12 - 19
Beans, Dark/ Light Red Kidney	13	0.16	0.20	0.05	11 - 20
Beans, Garbanzo	32	0.06	0.15	-0.01	7 - 16
Beans, Great Northern	12	0.14	0.13	-0.02	12 - 19
Beans, Large Lima	4	-0.02	0.05	-0.02	10 - 12
Beans, Pea	35	-0.14	0.12	0.00	12 - 21
Beans, Pink	9	-0.17	0.21	-0.02	10 - 19
Beans, Pinto	18	-0.14	0.14	0.00	9 - 18
Beans, Small Red	11	0.07	0.13	-0.01	10 - 19
Canola	15	0.00	0.12	-0.01	4 - 9
Corn	668	-0.01	0.41	0.00	7 - 42
Durum	130	0.00	0.18	0.00	5 - 19
Flaxseed	9	0.00	0.04	-0.01	7 - 9
Lentils	43	0.14	0.16	0.02	8 - 14
Mustard Seed, Oriental	4	0.10	0.45	-0.03	7 - 19
Mustard Seed, Yellow	10	-0.04	0.17	-0.02	5 - 11
Oats	66	0.00	0.28	-0.06	10 - 18
Peas, Smooth Green Dry	72	0.00	0.20	-0.01	9 - 16
Rice, Long Grain Brown	18	-0.08	0.14	-0.06	11 - 15
Rice, Long Grain Milled	27	0.09	0.13	0.03	12 - 14
Rice, Long Grain Rough	226	0.00	0.32	-0.01	10 - 26
Rice, Medium Grain Brown	34	-0.06	0.23	-0.13	10 - 15
Rice, Medium Grain Milled	20	0.04	0.17	0.08	12 - 14
Rice, Medium Grain Rough	139	0.00	0.35	-0.01	10 - 28
Rice, Short Grain Rough	18	0.00	0.46	-0.02	12 - 24
Rye	4	0.00	0.02	0.00	12 - 13
Safflower	30	0.00	0.20	-0.01	3 - 12
Sorghum	144	0.00	0.22	-0.01	10 - 24
Soybeans	345	0.00	0.20	-0.01	8 - 23
Sunflower Seed	226	-0.01	0.38	-0.02	5 - 20
Sunflower Seed, Confectionary	20	0.10	0.37	0.11	8 - 14
Wheat, Hard Red Spring	204	-0.02	0.20	-0.01	7 - 21
Wheat, Hard Red Winter	312	0.09	0.16	-0.02	7 - 19
Wheat, Hard White	79	0.09	0.15	-0.01	8 - 21
Wheat, Soft Red Winter	265	-0.04	0.16	0.00	9 - 22
Wheat, Soft White	149	-0.13	0.21	0.02	8 - 19

Details of Secondary Kernel-Density Correction

The secondary kernel-correction dramatically reduces the error for corn caused by unusually low kernel density. Figure 4 illustrates key aspects of the correction. The plot shows all the corn samples with the several low kernel density samples (blue diamonds) segregated from the "normal samples" (red +).

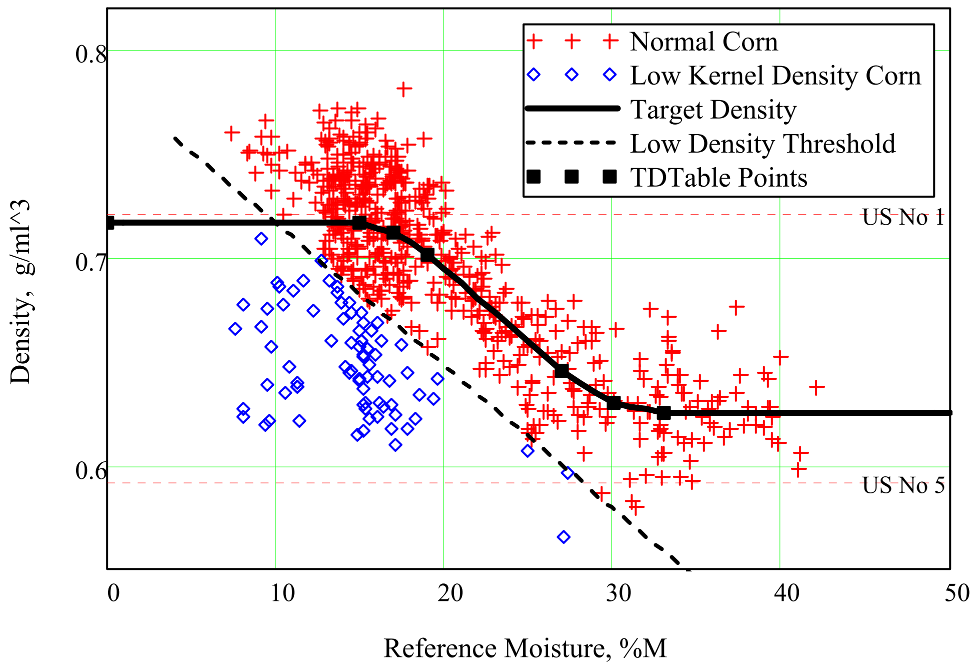


Figure 4. Target density curve (TDTable)

The separation or threshold function is by Eq. 11 and the dotted line in Figure 6.

$$LowDensityThreshold(\%M) = \left[\left(\frac{45-53}{30-15}\right) \cdot (\%M - 15) + 53\right] \cdot ConversionParameter \qquad (11)$$

ConversionParameter transforms the values from lb/bu to g/ml. Value= 0.01287.

Including the low kernel-density samples in the calibration causes significant errors both for the normal and low kernel-density samples. For optimizing the calibration for the normal samples, the low kernel density samples are not included in the calibration. The samples for which the kernel-density correction is zero lie on the solid line in Figure 4—the moisture-dependent target density (*TD*) curve. The predicted moisture error (correction to be applied) is proportional to the vertical distance between the sample density (*Mass*/*TestCellVolume*) and the target density (*TD*) curve.

So the correction is defined as:

$$SecDensCorr(Moisture3, Mass) = \left(\frac{Mass}{TestCellVolume} - TargetDensity\right) \cdot SlopeCorrection \qquad (8)$$

The slope correction factor *SC* (needed correction to density-distance ratio) is moisture-dependent. See Figure 5.

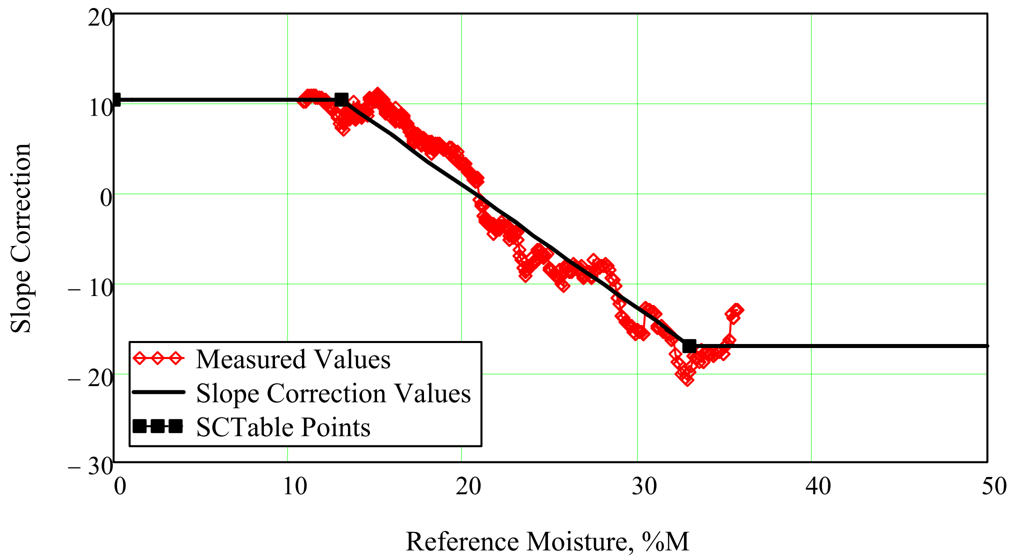


Figure 5. Slope correction values. Visualization of the *SC* Table.

Table 11 and Figure 6 show that by using the secondary kernel-density correction, the errors in predicted moisture for low kernel-density corn samples are significantly reduced. Furthermore, the standard deviation of the predicted moisture errors for "normal" samples is improved.

Table 11. Secondary kernel-density correction statistics; before (left) and after (right) correction

Samples.	**Mean Diff.**	**STD**	**Slope**
All	-0.03	0.51	0.00
Low Dens.	-0.6	0.46	0.05
Norm.	0.05	0.46	-0.01

Samples	**Mean Diff.**	**STD**	**Slope**
Overall	-0.01	0.41	0.00
Low Dens.	-0.09	0.33	0.00
Norm.	0.00	0.42	0.00

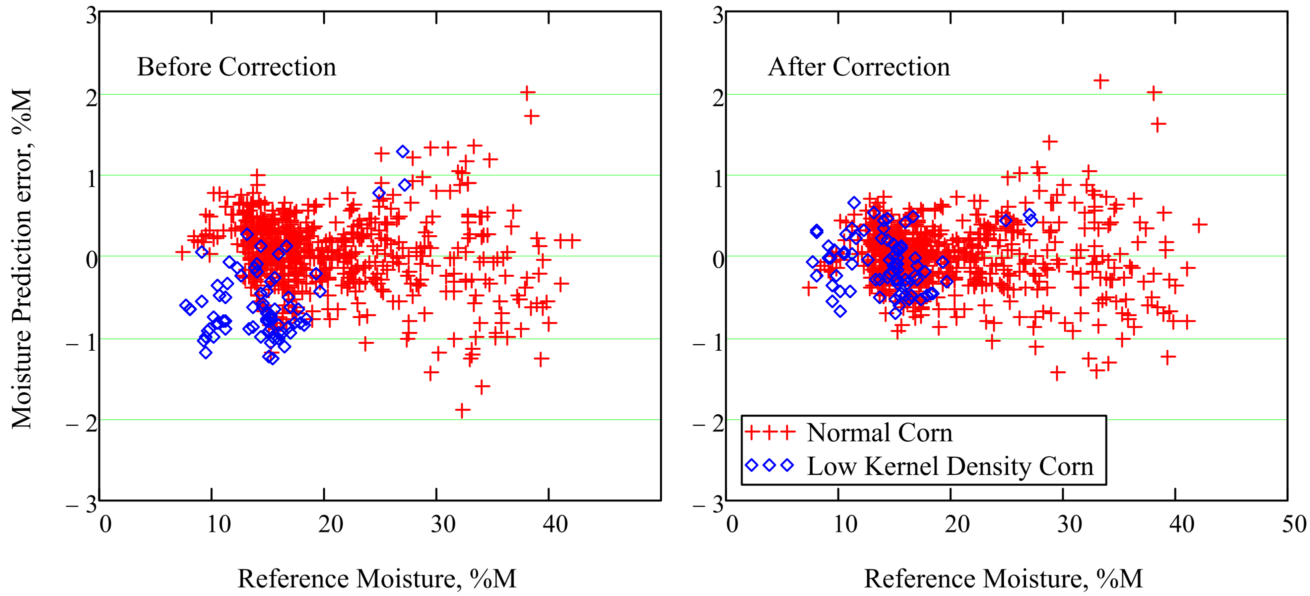


Figure 6. Corn sample predicted moisture errors before and after secondary kernel-density correction.

Sensitivity Analyses

1. **Measurement frequency sensitivity.** Our analysis evaluated two cases of frequency sensitivity: 1) the deliberate choice of a known frequency other than 149.00 MHz, and 2) imprecision or instability in the measurement frequency of specific moisture meters. The exact choice of measurement frequency is not terribly critical; a manufacturer may have reasons to choose a specific frequency to avoid interfering with or being influenced by known problematic signal sources or sensors in the environment. The change in dielectric constant values versus frequency is relatively small, so the same unifying parameters and calibration curve may be used over a limited frequency range. An evaluation with data for over 6000 samples of multiple grain types showed an average moisture error of -0.02% moisture per MHz for measurement frequency changes around 149 MHz. This sensitivity value assumed that the test cell model parameters (but not unifying parameters or calibration coefficients) were optimized for each test frequency. The second case assumes that the measurement frequency varied from the intended value, and that the test cell model parameters were not re-optimized for the specific measurement frequency. In this case, the frequency sensitivity was about ten times worse (+0.2% moisture per MHz of uncompensated measurement frequency error). For further information see: *Analysis of Frequency Sensitivity of the Unified Grain Moisture Algorithm*, ASAE Meeting Paper #053047, Zoltan Gillay and David Funk, 2005.
2. **Temperature measurement sensitivity.** Moisture measurement errors associated with temperature are due to temperature measurement errors and temperature correction function inadequacies. Typical temperature coefficients are about 0.1% moisture per degree Celsius difference from the reference temperature (22 or 25 °C). (See *KTC* values in Table 3.) If the sample temperature sensor has significant thermal mass or other characteristics that cause measurement error to degrade at temperature extremes, significant moisture errors may result. Temperature measurement accuracy at room temperature must be especially good to avoid contributing significantly to moisture measurement errors during routine in-field performance verification (check testing). The temperature correction function must be sufficiently robust to provide good corrections over the full intended temperature (and moisture) range. Systematic temperature measurement errors for an instrument model (which could be corrected through the selected temperature correction function) cannot be tolerated in official moisture meters, which must use the same set of official moisture calibrations.
3. **Ranges of interest for dielectric constant, density-corrected dielectric constant, and related factors.** The following plots illustrate the ranges of parameters and sensitivities that are relevant for Official grain moisture measurement.

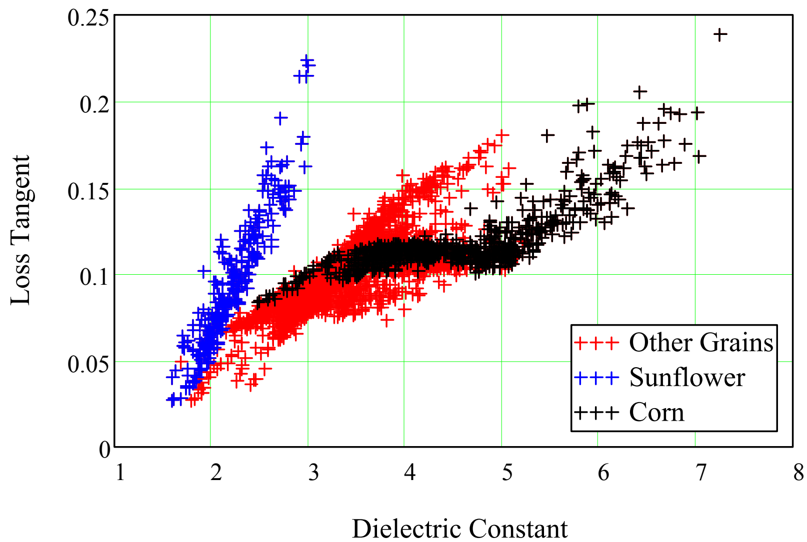


Figure 7. Loss tangent versus dielectric constant values for grains tested in 2008, 2009, and 2010 Calibration Studies.

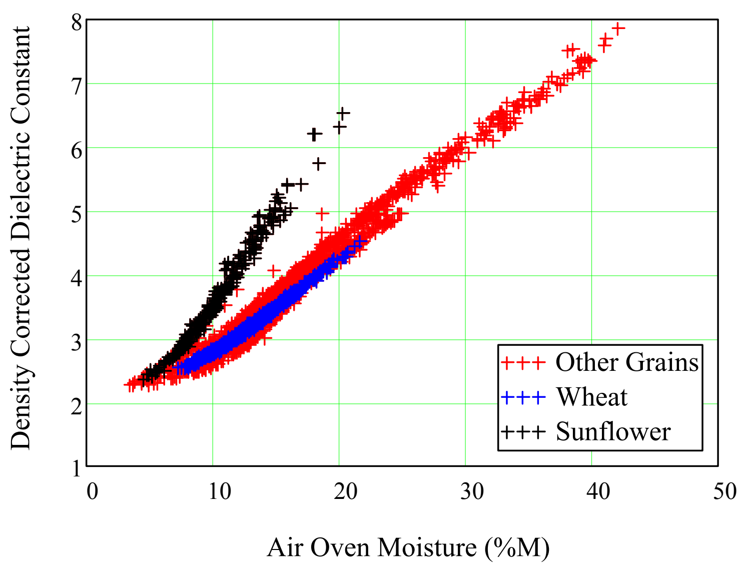


Figure 8. Density-corrected dielectric constant versus moisture values for grains tested in 2008, 2009, and 2010 Calibration Studies.

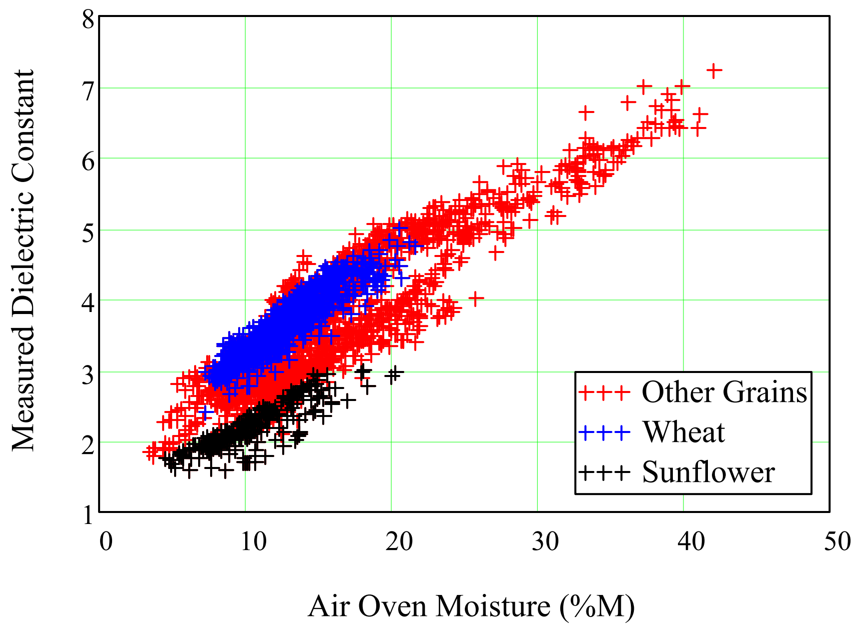


Figure 9. Measured dielectric constant values (prior to density correction) for grains tested in 2008, 2009, and 2010 Calibration Studies.

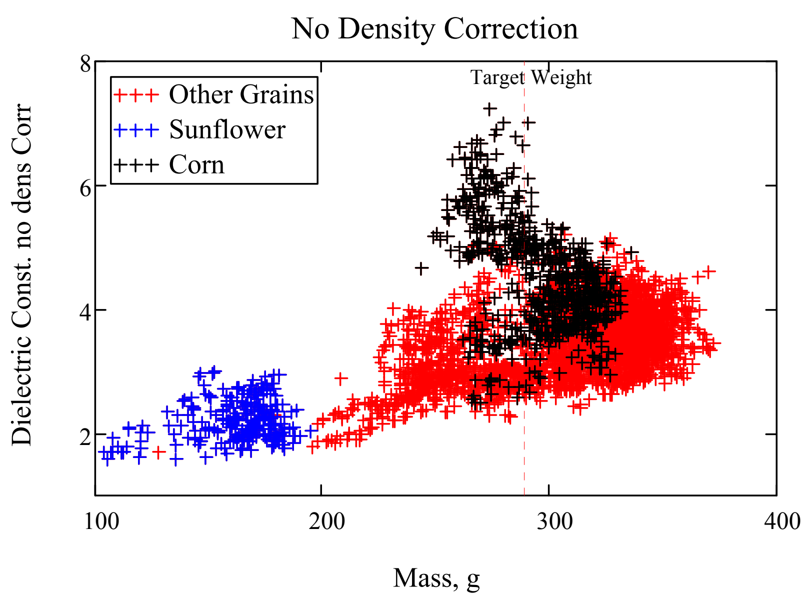


Figure 10. Measured dielectric constant values (without density correction) versus sample mass for grains tested in 2008, 2009, and 2010 Calibration Studies.

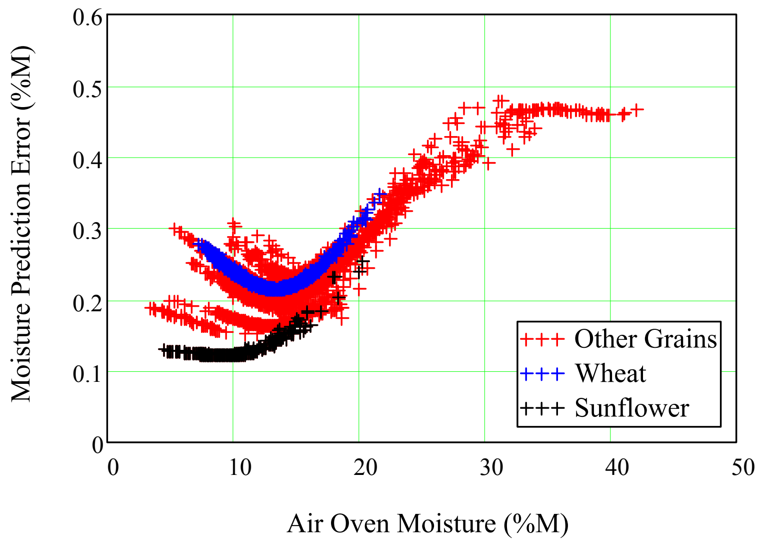


Figure 11. Moisture prediction errors resulting from 1% (of value) errors in density-corrected dielectric constant for grains tested in 2008, 2009, and 2010 Calibration Studies.

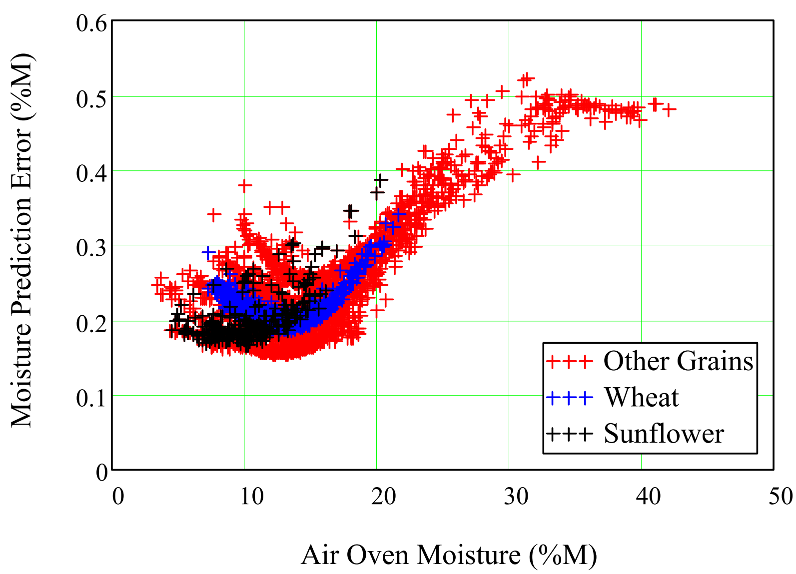


Figure 12. Moisture prediction errors resulting from 1% (of value) errors in measured dielectric constant for grains tested in 2008, 2009, and 2010 Calibration Studies.

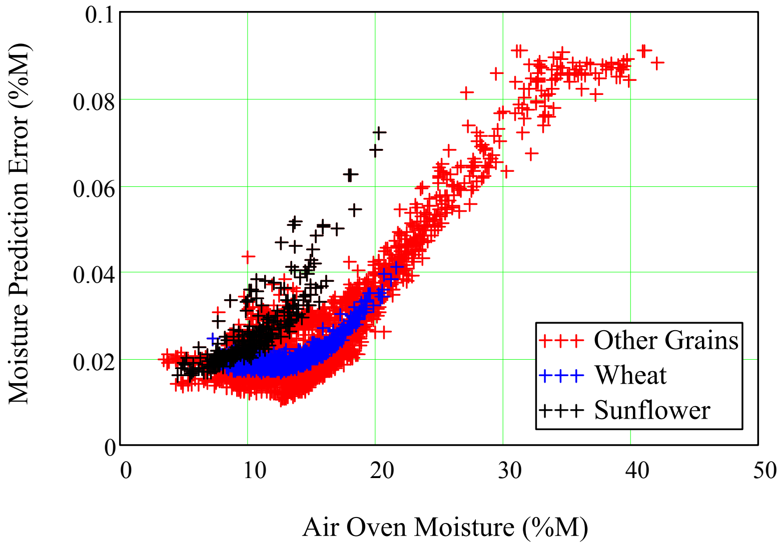


Figure 13. Moisture prediction error resulting from -0.3 gram mass measurement error for grains tested in 2008, 2009, and 2010 Calibration Studies. (A negative mass measurement error results in a positive moisture prediction error and vice versa.)

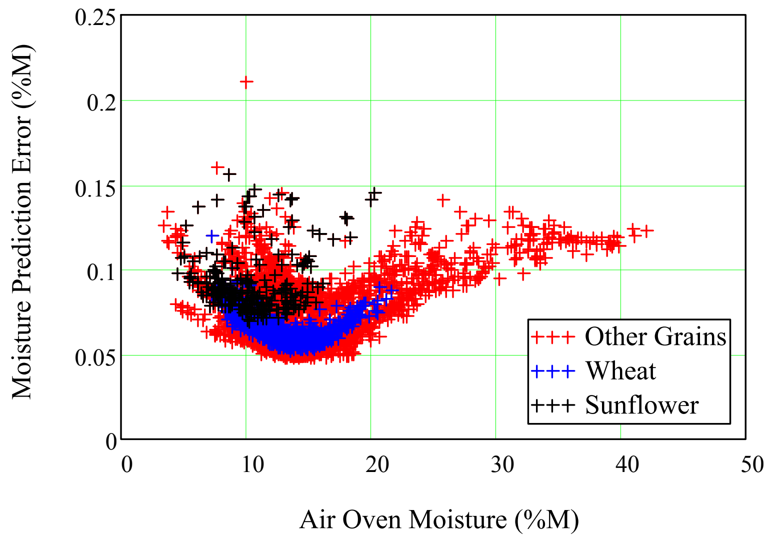


Figure 14. Moisture prediction error caused by a +1 mU error (not relative) in the magnitude of the measured reflection coefficient (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.)

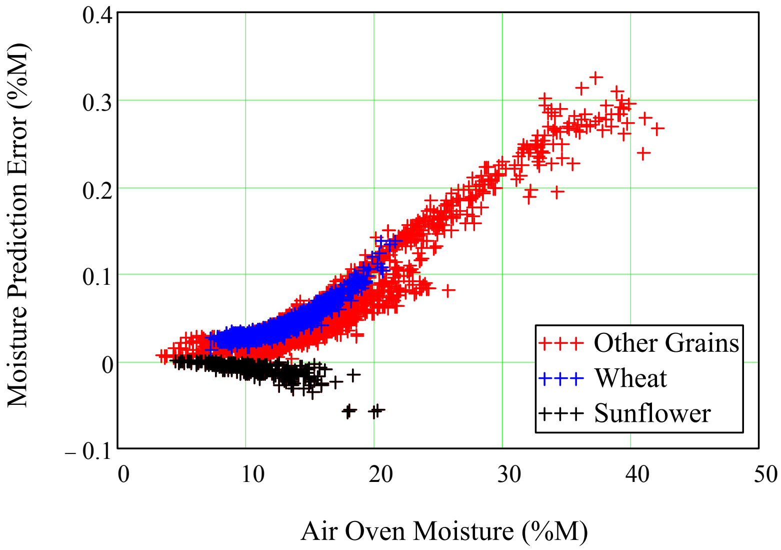


Figure 15. Moisture prediction error caused by a -1 degree error in the phase of the measured reflection coefficient (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.)

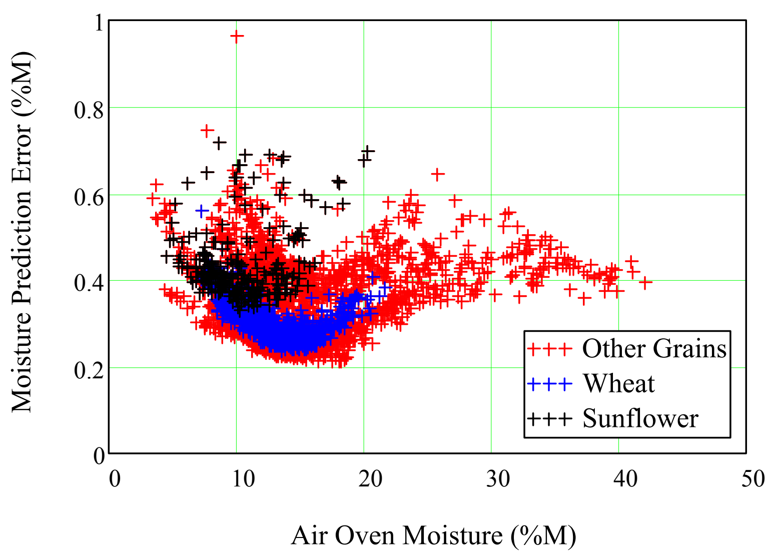


Figure 16. Moisture prediction error caused by a 1% (relative) error in the magnitude of the measured test cell complex impedance (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.)

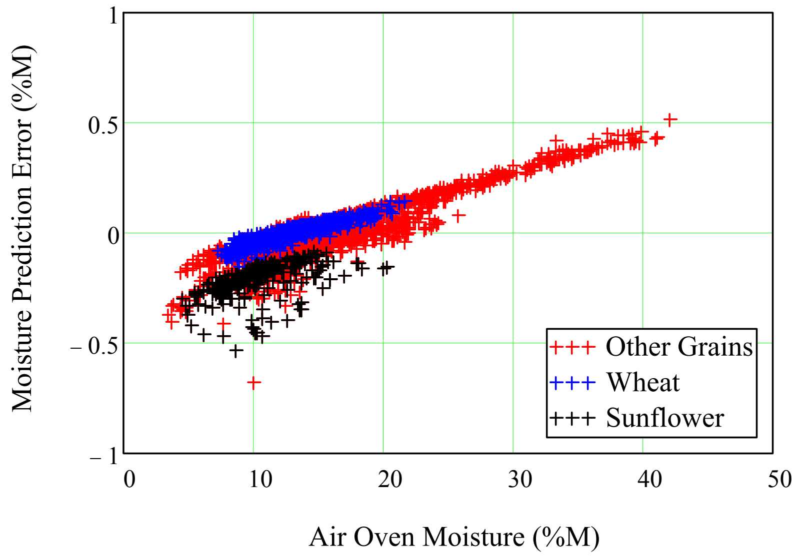
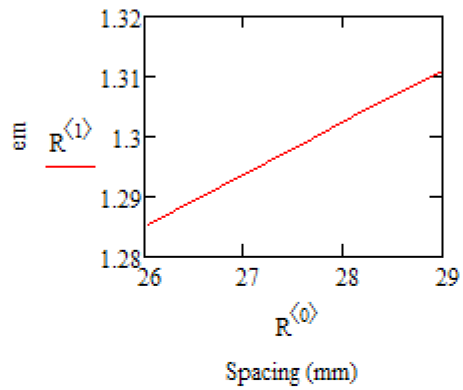


Figure 17. Moisture prediction error caused by a -1 degree error in the measured phase of the test cell impedance (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.)

Spacing predicting em

$$\mathrm{line}\left(R^{\langle 0\rangle}, R^{\langle 1\rangle}\right) = \begin{pmatrix} 1.05770 \\ 8.73573 \times 10^{-3} \end{pmatrix}$$

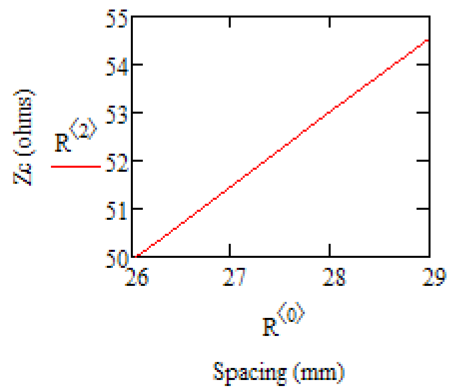
$$\mathrm{corr}\left(R^{\langle 0\rangle}, R^{\langle 1\rangle}\right) = 0.99999$$



Spacing predicting Zc

$$\mathrm{line}\left(R^{\langle 0\rangle}, R^{\langle 2\rangle}\right) = \begin{pmatrix} 9.87548 \\ 1.54056 \end{pmatrix}$$

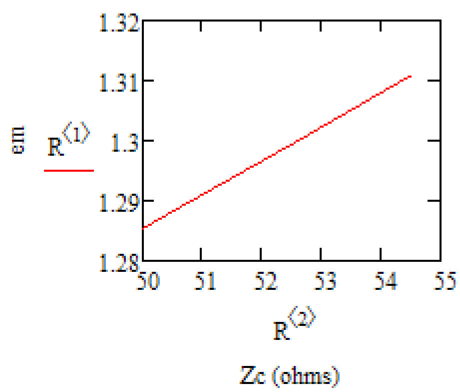
$$\mathrm{corr}\left(R^{\langle 0\rangle}, R^{\langle 2\rangle}\right) = 0.99999$$



Zc predicting em

$$\mathrm{line}\left(R^{\langle 2\rangle}, R^{\langle 1\rangle}\right) = \begin{pmatrix} 1.00170 \\ 5.67044 \times 10^{-3} \end{pmatrix}$$

$$\mathrm{corr}\left(R^{\langle 2\rangle}, R^{\langle 1\rangle}\right) = 0.99999$$



Spacing predicting Zc--air section

$$\mathrm{line}\left(R^{\langle 0\rangle}, R^{\langle 3\rangle}\right) = \begin{pmatrix} 10.726534 \\ 1.494043 \end{pmatrix}$$

$$\mathrm{corr}\left(R^{\langle 0\rangle}, R^{\langle 3\rangle}\right) = 0.99998$$

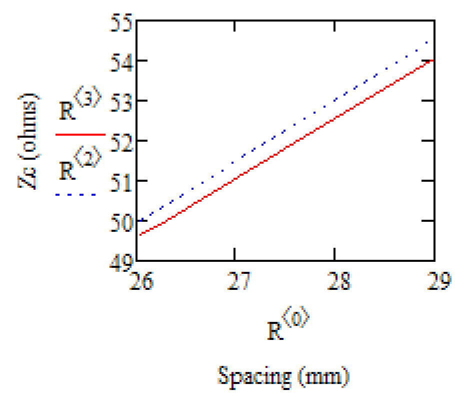


Figure 18. Relationships between test cell plate spacing, characteristic impedance, and filling factor. The relationships are highly linear. These results are from finite element analysis using the dimensions of the FGIS "New Master" (NM) test cell. Note that the "Spacing Predicting Zc—air section" analysis is based on a finite element model that includes the presence of the metallic base plate in the NM test cell, whereas the "Spacing Predicting Zc" analysis excludes the effects of the base plate. For the latter case, the effects of the base plate and the test cell gate are separately included in the test cell model as a constant offset term in the dielectric measurement.

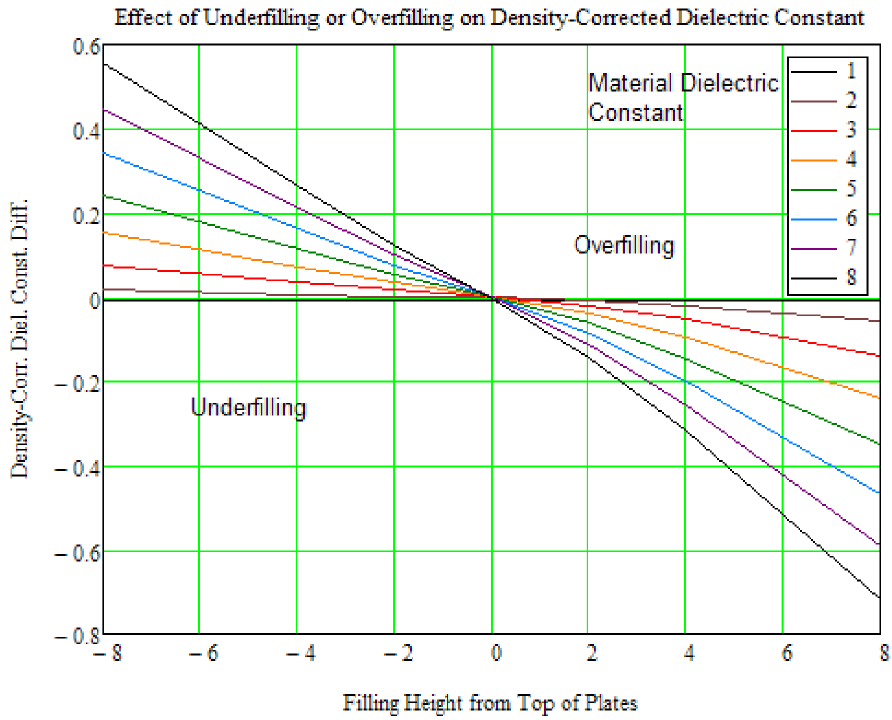


Figure 19. Estimated effects on density-corrected dielectric constant of overfilling and under-filling of the test cell (as a function of filling height in mm). These results are based on finite element analysis of the "New Master" test cell.

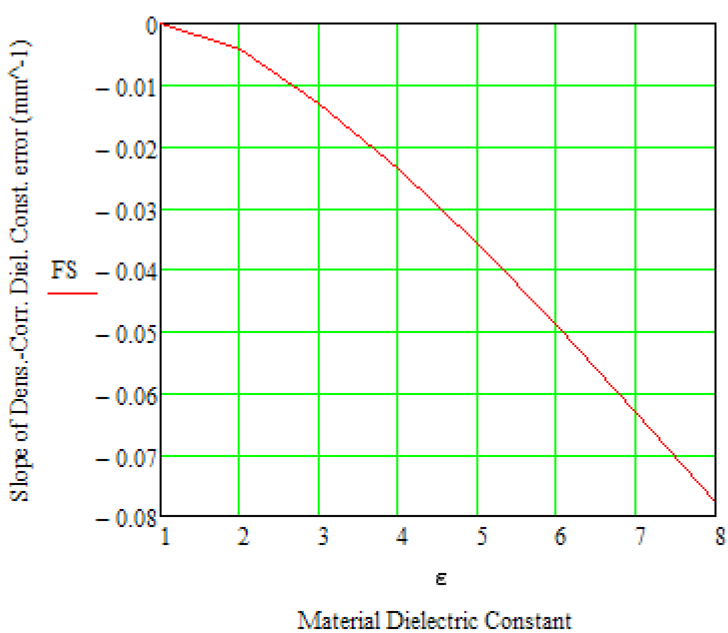


Figure 20. The slope of the density-corrected dielectric constant change with filling height (dielectric constant units per mm) based on finite element analysis of the New Master test cell.

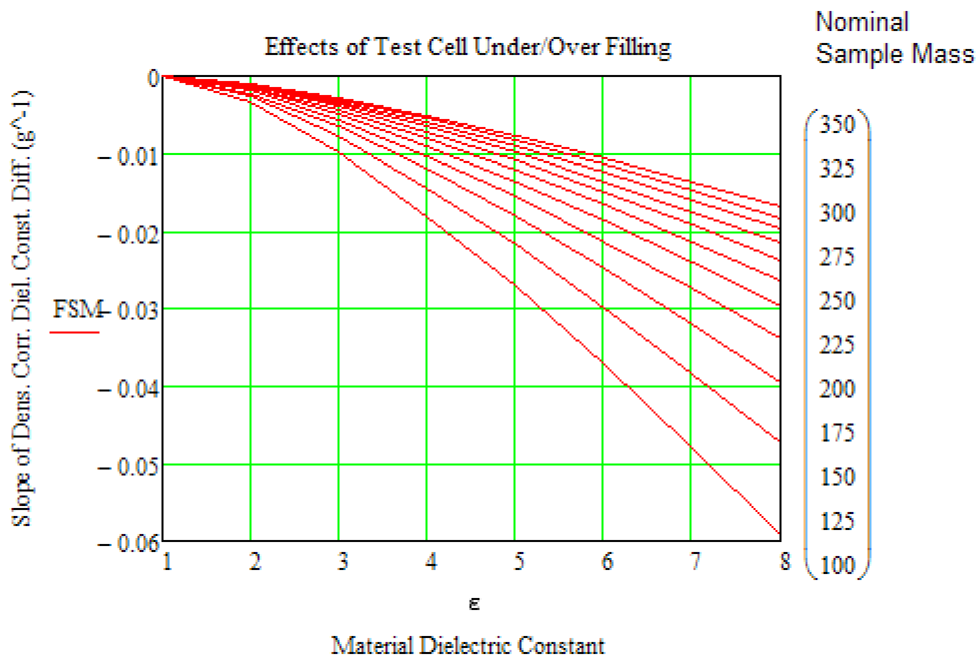


Figure 21. Plot of the slopes of density-corrected dielectric constant per gram of cell overfilling or under-filling. These results like those of Figs. 18-20 are based on finite element analysis of the New Master test cell.

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